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# Overview—DOE/NASA Automotive Gas Turbine and Stirling Projects

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AUTOMOTIVE GAS TURBINE AND STIRLING PROJECTS  
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Work performed for  
**U.S. DEPARTMENT OF ENERGY**  
**Conservation and Solar Energy**  
**Office of Transportation Programs**



Prepared for  
Heat Pump Contractors' Program Integration Meeting  
McLean, Virginia, June 2-4, 1981

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## OVERVIEW - DOE/NASA AUTOMOTIVE GAS TURBINE AND STIRLING PROJECTS

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### SUMMARY

This report presents a brief overview of the automotive gas turbine and automotive Stirling engine technology projects being carried out by NASA Lewis Research Center for the Department of Energy's Automotive Technology Development Division. This report: (1) discusses the projects as they were formulated and being carried out in accordance with PL 95-238 "Auto Propulsion Research and Development Act of 1978;" (2) presents substantive technology accomplishments, and (3) briefly addresses future path options of the program.

**The Projects.** A brief review of the project history since its inception by EPA in 1970 is presented in Fig. 1. Figure 2 shows the anticipated phasing of government and industry efforts leading from experimental engine technology by government/industry teams to eventual production by industry. The project goal is the same for both the gas turbine and Stirling engines and is presented in Fig. 3. The 30 percent fuel economy improvement is for vehicles of equivalent weight and performance. Accomplishments planned to be completed by the end of the development projects, in order to meet the project goals, are shown in Fig. 4. The project activities are divided into three major areas as shown in Fig. 5, with the major contractors, contract start dates, and contract values given in Fig. 6. (MTI/USS/AMC is a contractor team composed of Mechanical Technology Inc., United Stirling of Sweden, and AM General. DDA is Detroit Diesel Allison Division of General Motors.) The first three contracts listed are engine development efforts; the fourth "Ceramic Applications In Turbine Engines" involves incorporating ceramic components into an existing heavy duty truck gas turbine to obtain early field experience with ceramic components. The three engine development contracts follow the same development logic with similar schedules as shown in Fig. 7, with a Reference Engine design effort to guide the overall effort, component technology development, and two generations of engines (Mod I and Mod II) to be tested both on dynamometers and in vehicles.

**Technology Accomplishments-Gas Turbine.** Key technology requirements for the successful development of the automotive gas turbine engine are listed in Fig. 8. Figure 9 is a cutaway view of the single shaft gas turbine design under development by Garrett/Ford. The DDA design is a two-shaft machine, and both utilize radial flow turbomachinery. Status and significant accomplishments of the automotive gas turbine project are presented in Figs. 10 to 12.

For the automotive gas turbine, ceramics are the key to high performance. This is illustrated in Fig. 13. Figure 14 presents a cutaway view of the Detroit Diesel Allison heavy duty turbine engine which is being modified with the ceramic components identified in the figure.

This effort is being carried out in three steps of increasing turbine inlet temperature as shown in the schedule in Fig. 15. Maximum temperature requirements and candidate materials for key ceramic components of the automobile engines under development are given in Fig. 16. Two sample ceramic rotors fabri-

cated by Carborundum for the DDA automobile engine gasifier turbine are shown in Fig. 17. These rotors are visually and dimensionally acceptable but do not yet meet the strength requirements. Figure 18 illustrates one of the critical problems with the use of ceramics components. That is, the very small critical flaw size as compared to that for metal parts. This requires the development of new nondestructive evaluation techniques to be able to detect defective parts. As shown in Fig. 19 the ACT/CATE program is now the primary support of the U.S. structural ceramics effort. The areas of ceramic technology advancements still required are shown in Fig. 20.

### Technology Accomplishments-Stirling

Figure 21 lists some observations regarding Stirling engine technology status at project inception. This was in sharp contrast to the broad gas turbine technology base existing in this country. The United Stirling P-40 engine, Fig. 22, an experimental four cylinder, double acting engine, has served as the baseline engine for the automotive Stirling development effort. Key technology requirements of the automotive Stirling project are listed in Fig. 23. Figure 24 shows the participants in the major Stirling engine development contract and their primary area of responsibility. Early in the program a P-40 engine was installed in an Opel automobile, Fig. 25. While this resulted in an underpower, overweight vehicle, it was done to provide early engineering experience with engine-vehicle integration. Status and significant accomplishments of the automotive Stirling project to date are shown in Figs. 26 and 27. Figure 28 is a picture of the partially assembled Mod I Stirling engine now on test at United Stirling. Some very early Mod I engine test data at part power operating conditions is shown in Fig. 29. United Stirling anticipates little difficulty in achieving the design efficiencies with only minor corrections. Figure 30 illustrates a technique, developed in the supporting research and technology (SRT) effort at LeRC, for controlling the permeability of hydrogen through the high temperature metal heater tube walls. Current efforts are underway to determine how small a percentage of CO or CO<sub>2</sub> dopant can be utilized while still holding permeability losses within acceptable limits. Figure 31 is a picture of the Ground Power Unit (GPU), a single cylinder, displacer type engine originally built by General Motors, being used in the SRT effort at LeRC to evaluate new component technologies. Figure 32 shows a jet shell heat transfer device currently being tested in the GPU to assess its potential for augmenting heat transfer to the engine heater tubes.

**The Future Path.** Figure 33 addresses near term activities aimed at phasing the gas turbine and Stirling efforts down to the levels required by the administration's current budget plans. At the same time, an effort is being made to retain some flexibility of options should legislative action result in somewhat higher budget levels. While planning is still in the early stages, it is anticipated that the focus of technology effort starting in FY 82, Fig. 34, will shift from engine development to component technology, with emphasis on the longer range, high pay off technologies.

FY1978	79	80	81	82	83	84	85	86	87	88	89	90	91
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EXPERIMENTAL ENGINE • TECHNOLOGY

**GOV'T/IND**

## INDUSTRY

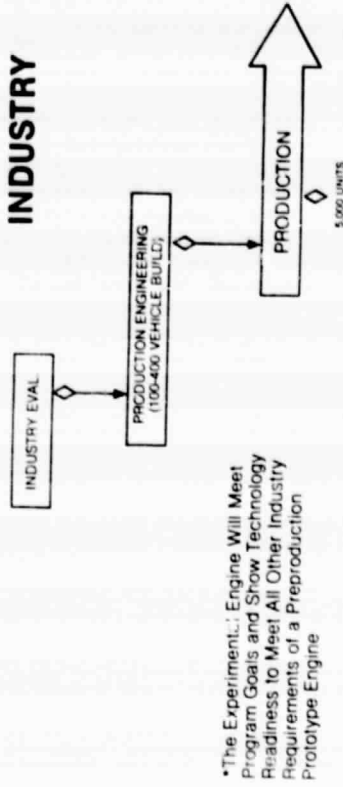


Figure 2. - Automotive heat engine technology.

- EXPERIMENTAL GAS TURBINE AND STIRLING PROPULSION SYSTEMS IN VEHICLES MEETING FUEL ECONOMY EMISSIONS AND MULTIFUEL CAPABILITY OBJECTIVES
- TEST STAND DURABILITY DATA FOR KEY COMPONENTS AND EARLY VERSIONS OF EXPERIMENTAL SYSTEMS
- PROJECTIONS BY INDUSTRY OF MASS PRODUCTION AND OWNERSHIP COSTS
- DEFINITION OF KEY LOW-COST MANUFACTURING APPROACHES

**Figure 4. - Accomplishments by end of development projects.**

- EPA REQUEST TO LERC FOR EMISSION TECHNOLOGY HELP IN 1970.
- EPDA-NASA IAA IN 1976 FOR HEAT ENGINE TECHNOLOGY PROJECT MANAGEMENT - CHANGED TO DOE-NASA IN 1977
- TRANSPORTATION PROPULSION DIVISION WITH GAS TURBINE & STIRLING PROJECT OFFICES FORMED AT LERC IN 1977.
- TITLE III, PL 95-238 IN FEB 1978 MANDATED DOE TO DEVELOP GAS TURBINE & STIRLING EXPERIMENTAL ENGINE TECHNOLOGIES WITHIN 5 YEARS - AND AMENDED SPACE ACT FOR NASA PARTICIPATION.
- MAJOR TECHNOLOGY DEVELOPMENT CONTRACTS SIGNED IN 1979-1979.

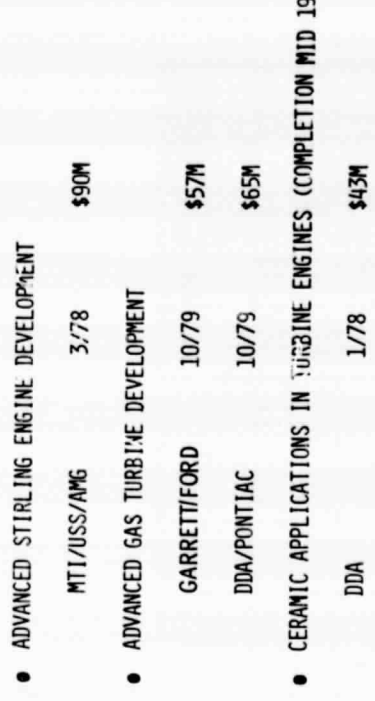
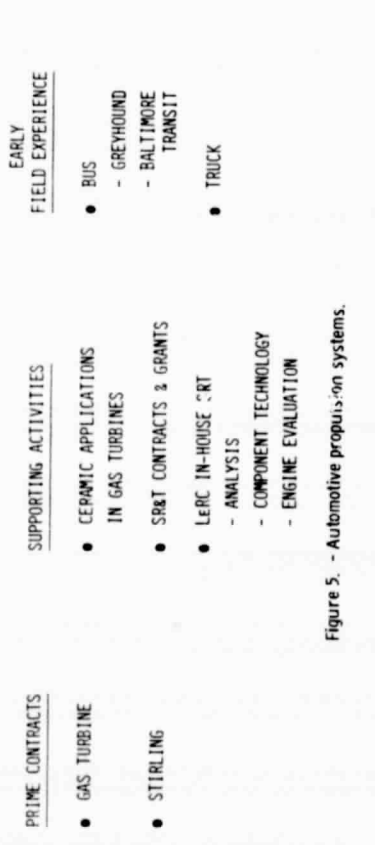
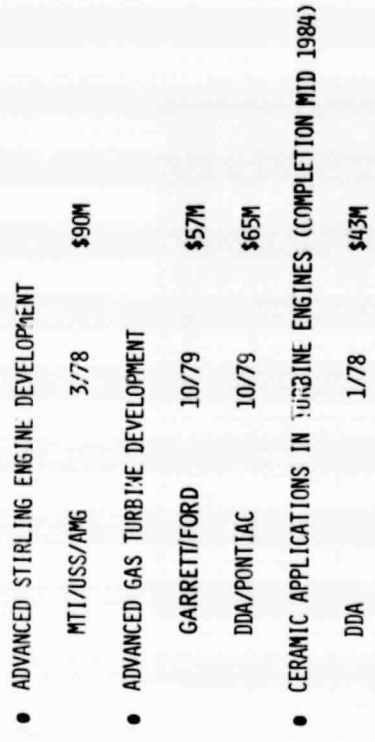
Figure 1. - Some history.

**OVERALL GOAL:**

PROVIDE THE TECHNOLOGY BASE WITHIN THE AUTO INDUSTRY TO SUPPORT PRODUCTION DEVELOPMENT OF ALTERNATE AUTOMOTIVE PROPULSION SYSTEMS THAT:

- SHOW AT LEAST 30 % FUEL ECONOMY GAINS OVER SPARK IGNITION ENGINE
- MEET MOST STRINGENT EMISSIONS STANDARDS INCLUDING .4 GM/MI NO<sub>x</sub>
- CAN USE A VARIETY OF FUELS INCLUDING NONPETROLEUM BASE
- CAN BE SOLD COMPETITIVELY

Figure 3. - Heat engine program gas turbine and stirling.



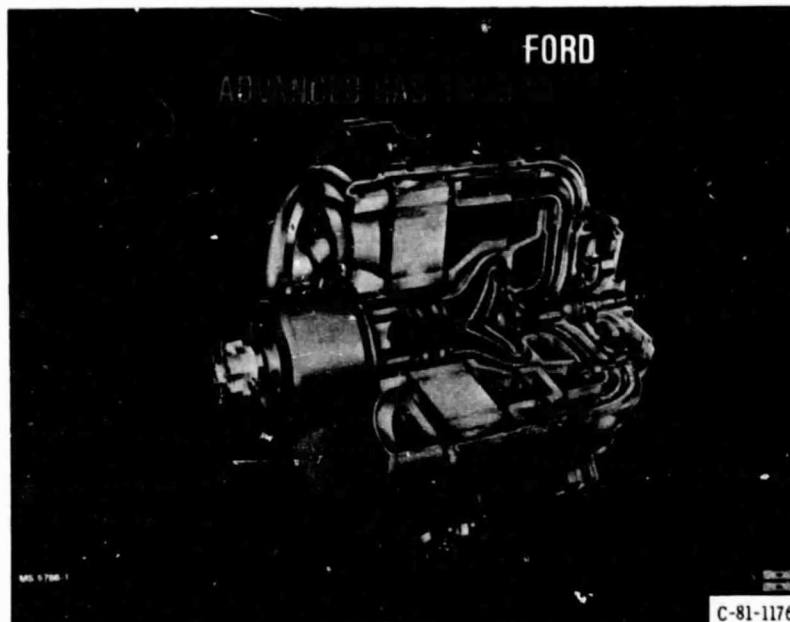


Figure 9.

- GARRETT/FORD PRELIMINARY DESIGN SHOWS ADVANCED POWERTRAIN SYSTEM POTENTIALLY CAPABLE OF MEETING PROJECT OBJECTIVES.
- FIRST MOD I BUILD IN AUGUST
- DDA/PONTIAC DESIGN REVIEWS IN JUNE
- RESULTS OF RECENT TURN-AROUND ON WEIGHT/COST/HEAT LOSS ISSUE WERE JUST EXCELLENT - COST POTENTIAL NOW FITS ACCEPTABLY IN GM'S 1985-90 MARKET PROJECTIONS.
- COMPRESSOR TESTS ARE ABOVE PART-POWER EFFICIENCY TARGET FOR MOD 2!

Figure 10. - Automotive gas turbine status and significant accomplishments.

- CERAMICS (THE KEY TO ULTIMATE SUCCESS)
  - 6657 MILES SUCCESSFULLY RUN OVER-THE-ROAD WITH AN ENGINE WITH CERAMIC TURBINE VANES & REGENERATOR CORES
  - VISUALLY GOOD. DIMENSIONALLY CORRECT. ONE-PIECE CERAMIC ROTORS FABRICATED
  - OVER 700 HOURS OF ENGINE TESTING OF INTEGRATED (36 PIECE) TURBINE NOZZLE COMPLETED (AT 1900° F T.I.T.)
  - 30,000 CYCLES (489 HOURS) TO 2200° F COMPLETED ON ONE PIECE SILICON NITRIDE TURBINE STATOR
  - OVER 5000 HOURS OF SUCCESSFUL OPERATION ON 4 CERAMIC REGENERATOR CORES AT 1300° F IN AN ENGINE
- KEY TECHNOLOGIES
  - ALL COMPRESSOR & TURBINE DATA MEETING INITIAL GOALS
  - ULTRA-LEAN COMBUSTOR CONCEPT SHOWS PROMISE FOR SIMPLER, LOWER COST HARDWARE
  - CATALYTIC COMBUSTOR MATERIAL SHOWS GOOD PERFORMANCE AND DURABILITY FOR 250 HOURS AT 2600° F

Figure 12. - Automotive gas turbine status and significant accomplishments.

Figure 11. - Automotive gas turbine status and significant accomplishments.

ENGINE TECHNOLOGY LEVEL	PROJECTED FUEL ECONOMY, MPG*
BASILINE TECHNOLOGY (CHRYSLER UPGRADED ENGINE)	18.4
AGT METAL ENGINE (MOD 1)	26.0
AGT CERAMIC ENGINE (MOD 2)	42.5

\* DIESEL FUEL, 3000 LB VEHICLE

Figure 13. - The payoff of ceramics technology for an automotive gas turbine engine.



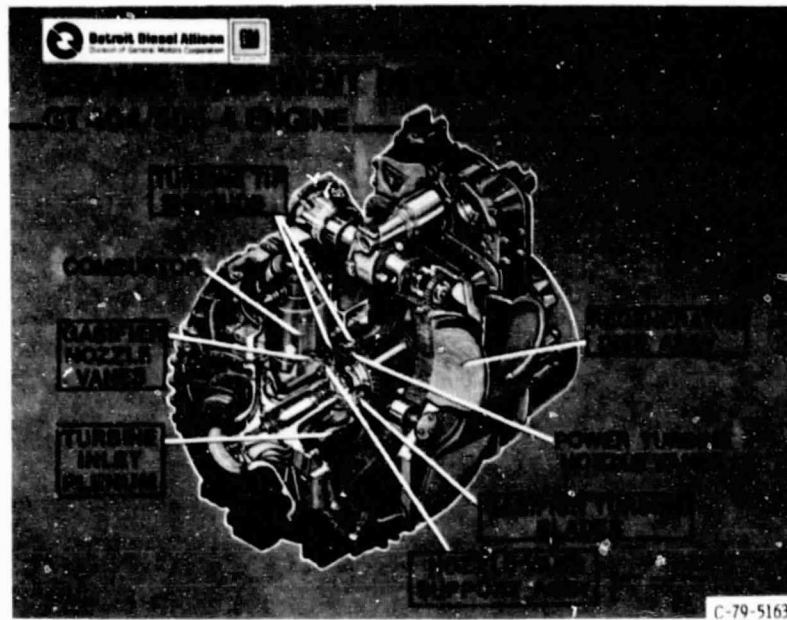
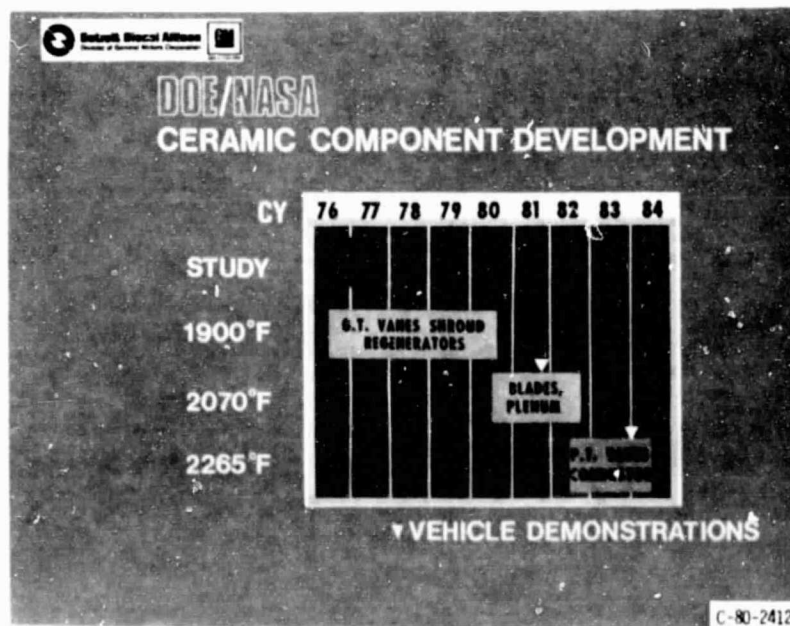


Figure 14.








TURBINE		2200 <sup>0</sup> F NOMINAL (2350 <sup>0</sup> MAX) HIGH STRESS	SiC OR Si <sub>3</sub> N <sub>4</sub>
VANES		2500 <sup>0</sup> F NOMINAL (2600 <sup>0</sup> F MAX)	SiC
COMBUSTOR		2600 <sup>0</sup> F MAX	SiC
SCROLLS		2600 <sup>0</sup> F MAX	SiC
REGENERATOR		2000 <sup>0</sup> F MAX	AS, MAS LAS

Figure 16. - AGT key ceramic parts.



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Figure 17.

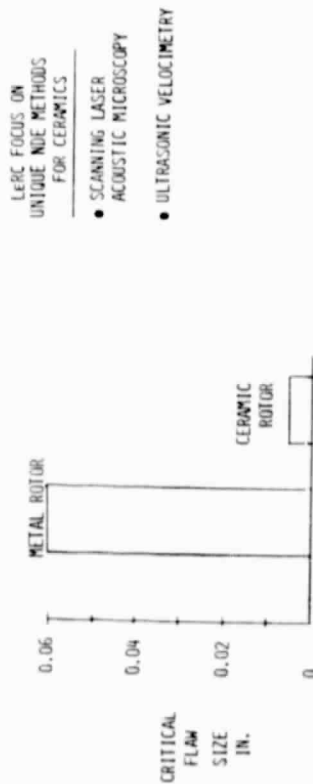


Figure 18. - Nondestructive evaluation: A key need for brittle materials.

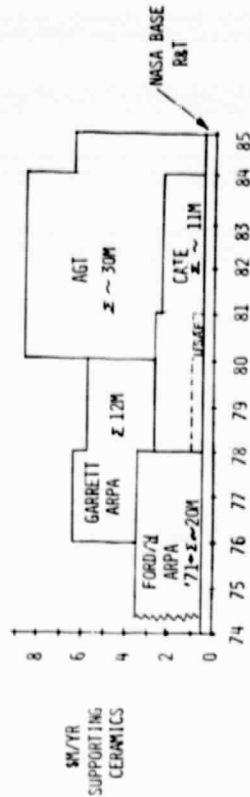


Figure 19. - AGT/CATE now major supporters of U. S. structural ceramics technology.

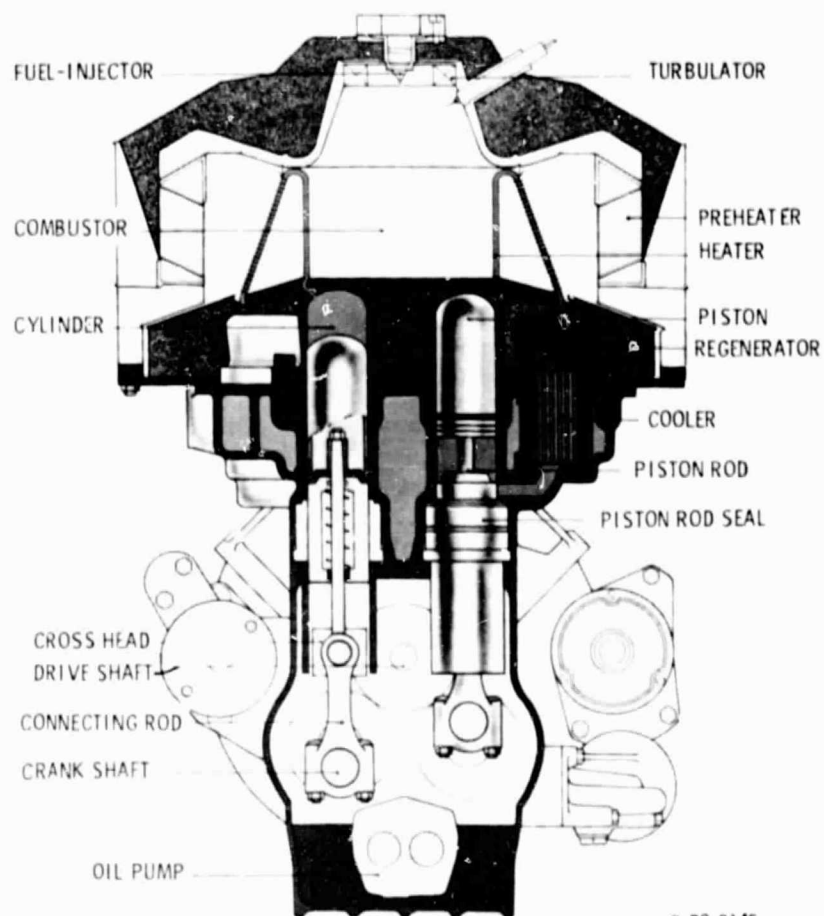
- MATERIAL PROPERTY IMPROVEMENTS
  - STRENGTH/REPRODUCIBILITY
  - ENVIRONMENTAL RESISTANCE
- PART QUALITY REPRODUCIBILITY
  - UNIFORM PROPERTIES
  - DIMENSIONAL CONTROL
- RELIABILITY/NDE

Figure 20. - Considerable ceramic technology advances still required.

- AN ESTABLISHED TECHNOLOGY BASE FOR STIRLING SIMILAR TO OTTO, DIESEL, RANKINE, OR GAS TURBINE DOES NOT EXIST.
- STIRLING TECHNOLOGY IS NOT PRESENTLY MATURE ENOUGH TO COMPETE COMMERCIALY IN MAJOR ENERGY ARENAS LIKE INDUSTRIAL OR AUTOMOTIVE APPLICATIONS WITHOUT SIGNIFICANT COMPONENT AND SYSTEM DEVELOPMENT.
- THERE IS A LIMITED NUMBER OF U.S. INDUSTRY PARTICIPANTS FOR ANY SUCH DEVELOPMENT PROGRAM BECAUSE OF LIMITED ACCESS TO: (A) DESIGN COMPUTER CODES; (B) ENGINE HARDWARE, AND (C) ENGINE OPERATING DATA.
- THERE IS NOT YET A RELIABLE, PROVEN ENGINE FOR TEST OR FOR DEVELOPMENT TOWARD A NEW APPLICATION, AND RELATIVELY LITTLE ENGINE OPERATING EXPERIENCE.
- MOST TECHNOLOGY EXISTS IN EUROPE.
- STATIONARY INDUSTRIAL AND SOLAR APPLICATIONS MUST EVOLVE FROM MAJOR AUTO PROGRAMS.

BUT THE ENGINE HAS GREAT POTENTIAL

Figure 21. - Observations regarding stirling technology status.



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Figure 22.

- LOW COST MATERIALS FOR HOT COMPONENTS
- REDUCED HYDROGEN PERMEABILITY
- LONG LIFE, LOW LEAKAGE, LOW FRICTION SEALS
- IMPROVED COMBUSTOR EFFICIENCY
- IMPROVED AUXILIARY EFFICIENCIES
- REDUCED DRIVEAWAY TIME
- ENGINE WEIGHT REDUCTION

Figure 23. - Automotive stirling engine project key technology required.

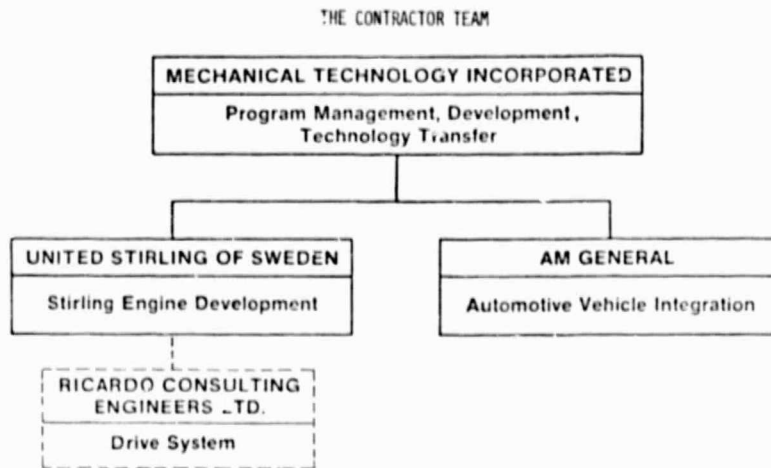


Figure 24. - Automotive stirling engine development program.



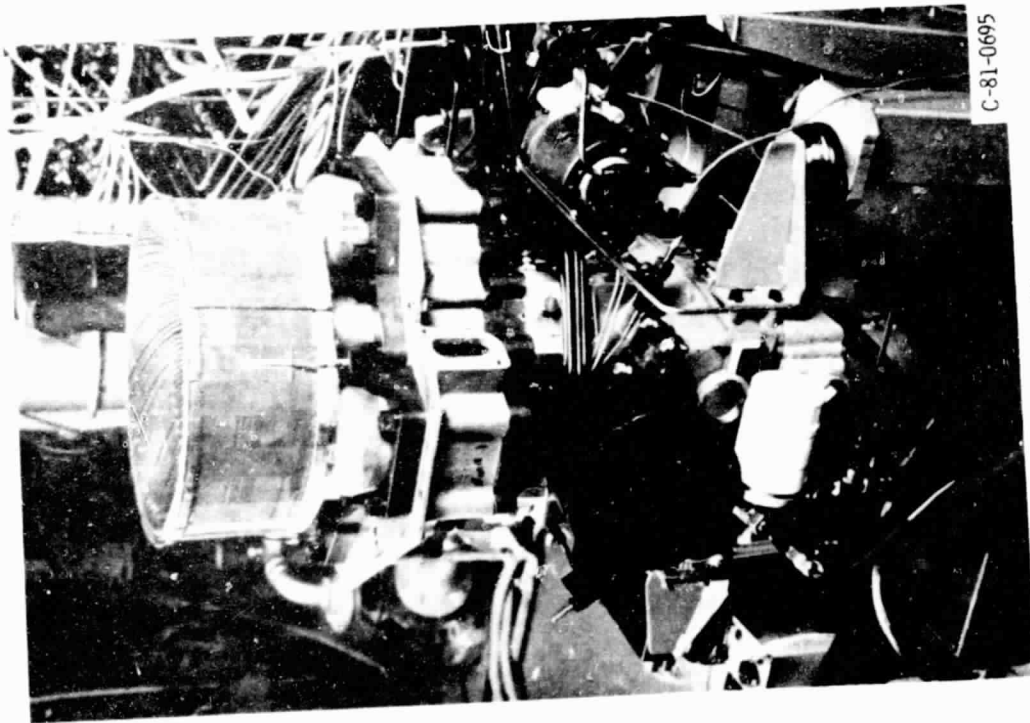
Figure 25.

- FIRST ENGINE DESIGNED FOR AUTOMOBILE (MOD-1) UNDER TEST -  
6 MORE TO FOLLOW
  - 147 HRS. AS MOTORING UNIT
  - 36 HRS. TESTING AT FULL TEMP - (BUT LOW PRESSURE)
  - PERFORMANCE WITHIN 2 POINTS OF PREDICTED WITH  $H_2$ ,  
BETTER WITH  $H_2$
  - NO MAJOR PROBLEMS
  - MOD-1 GOAL OF 20 % BETTER FUEL ECONOMY SHOULD BE ACHIEVED.
- ACHIEVED 0.3 GM/M  $NO_x$  WITH MOD-1 COMBUSTOR RIG (GOAL IS  $<0.4$  GM/M  $NO_x$ )
- STIRLING TECHNOLOGY TRANSFERRED TO U.S.
  - MTI, AMG, & LEWIS PERSONNEL ALL CAPABLE OF DIAGNOSING &  
CORRECTING ENGINE PROBLEMS
  - U.S. NON-PROPRIETARY PERFORMANCE & OPTIMIZATION CODES  
NOW EXIST
  - MOD-1 ENGINE BEING MANUFACTURED IN U.S.

Figure 26. - Automotive stirling status and significant program accomplishments to date.

- PROJECTED FUEL ECONOMY FOR THE REFERENCE ENGINE IN A 1984 "X"  
BODY CAR IS 42 MPG (GASOLINE - 56 % IMPROVEMENT OVER 1984 S.I.  
ENGINE IN SAME VEHICLE.
- TECHNICAL CHALLENGES IN STIRLING APPEAR CAPABLE OF SOLUTION
  - LEWIS INVENTION OF DOPING REDUCES  $H_2$  PERMEATION TO  
ACCEPTABLE LEVELS
  - PUMPING LENINGRADER ROD SEAL VERY GOOD
    - 3500 HOURS ON SEAL ASSEMBLY IN ENGINE
    - OVER 70,000 HRS. TOTAL EXPERIENCE ON SEAL
  - MATERIALS BEING DEVELOPED THAT SHOULD HAVE SUFFICIENT HOT  
STRENGTH WHILE STILL LOW IN COST
  - LERC 4-CYLINDER DYNAMIC CONTROLS MODEL IS ONLY SUCH CODE  
IN EXISTENCE.

Figure 27. - Automotive stirling status and significant program accomplishments to date.



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Figure 28.

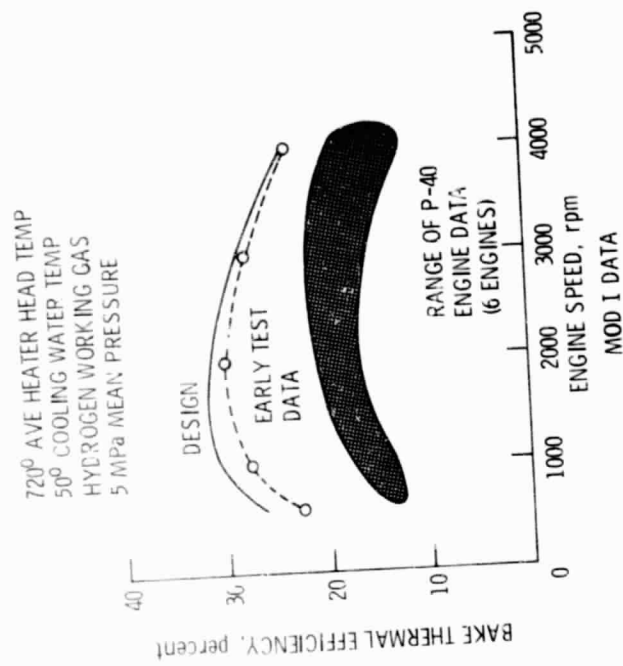


Figure 29. - (Low power operation.)

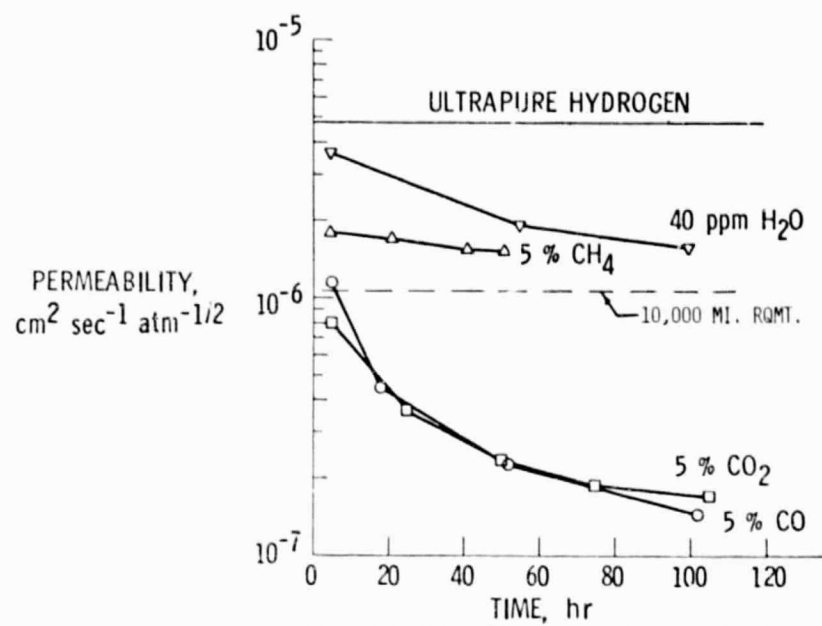


Figure 30. - Effect of dopants on hydrogen permeability through Inconel 800H.

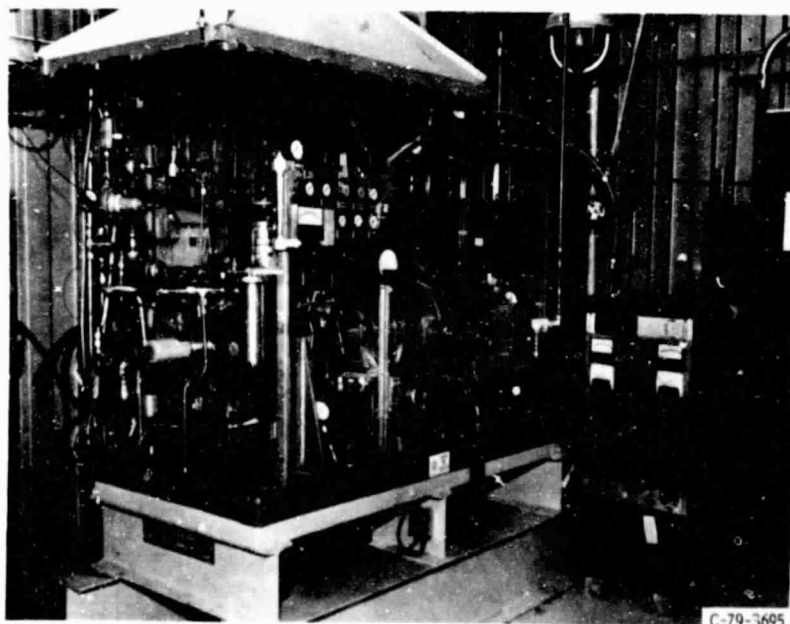
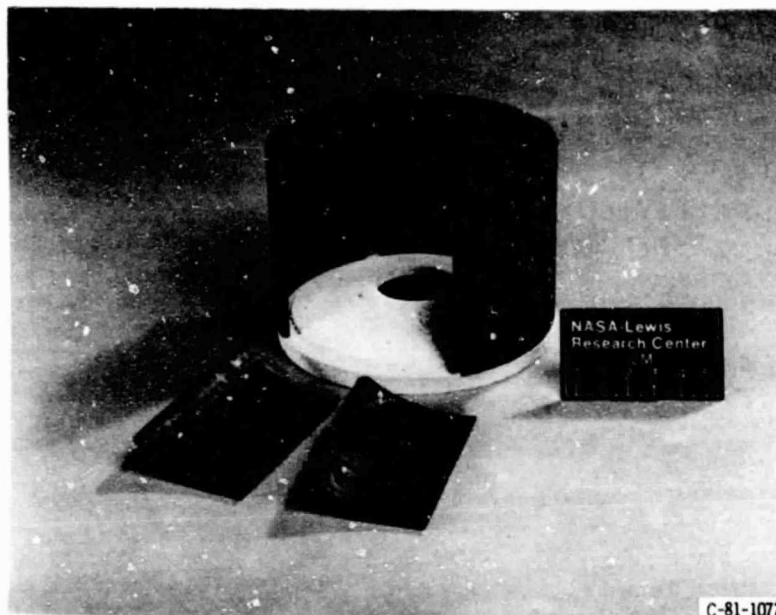


Figure 31.

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Figure 32.

- INITIATE PHASE DOWN OF TECHNOLOGY DEVELOPMENT ACTIVITIES IN FY 81 AS RATIONALLY AS POSSIBLE
- MAINTAIN OPTION FOR CONGRESSIONAL REINSTATEMENT
- INITIATE DEFINITION OF FY 82 REDUCED LEVEL TECHNOLOGY PROGRAMS
- GO-NO-GO DECISION POINT WILL OCCUR THIS SUMMER
- IF CURRENT MAJOR CONTRACTS ARE TO BE TERMINATED, ISSUE TECHNOLOGY RFP'S IN OCTOBER
- GAS TURBINE (~ \$3M)
  - CERAMICS FOCUS
  - SMALL SCALE AERODYNAMICS
  - USE MOD-I TEST BED
- STIRLING (~ \$3M)
  - CERAMIC HEATER HEAD
  - ADVANCED CONCEPTS - VARIABLE STROKE
  - SEALS, REGENERATORS

Figure 33. - The future path.

Figure 34. - The technology path (still in early planning stage).